# Debris Throw from Overloaded Concrete Structures at Internal Detonation under Shock, Blastimpulse and Gaspressure

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**Abstract**

The presentation belongs to the effort to get a PC based program to predict the debris throw in case of an accidental explosion in aboveground ammunition storage houses. Concrete structures will be overloaded by internal detonation. Overloading results in catastrophic failure and debris throw. Depending on the loading density and the charge arrangement 3 different fragmentation processes arise:

- Local composite shock *overloading* causes a spall crater, scabbing and penetration
- Areal blastimpulsive *overloading* causes shear and punching failure
- Volumetric gaspressure *overloading* blows the structure up and causes bending failure

Any of the processes results in debris throw. The mass and shape of debris as well as the launch velocity and launch angles will be different. The available DISPRE2 database is valid for gaspressure overloading at loading density $Q/V < 1\ kg/m^3$. It must be extended to cover composite shock overloading situations at loading densities $Q/V > 8\ kg/m^3$. Experiments were done in the DPM program (Debris Program Meppen, 1995) with unreinforced concrete slabs to demonstrate overloading mechanismes. A videofilm on the DPM program is part of the presentation.

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## 1. Introduction

The presentation belongs to the Klotz Club´s effort to get a PC based program to predict the debris throw in case of an accidental explosion in aboveground ammunition storage houses. The available program DISPRE2 works for charge mass up to Q = 5000 kg or loading density up to Q/V = 1 kg/m$^3$ in earthcovered, hardened aircraft shelters (HAS). It was the goal to develop a debris prediction methodology also for ammunition storage houses. Some hundred tons of different type of munition can be stored. Typical loading densities are Q/V = 8 kg/m$^3$ to 75 kg/m$^3$.

- The point that will be discussed is that extrapolating the available DISPRE2 empirical data base to high loading situations is not possible. The DISPRE2 database must be extended to cover specific differences between low loading and high loading situations. Only few empirical data is available. The DPM experiments were planned to do one step to an acceptable database.

The fragmentation of concrete structures will be discussed in terms of ***„overloading“***. Overloading results in catastrophic failure *and* debris throw. The internal loading was so high that a component loses its material integrity and/or the structure loses its structural integrity. Additionally the debris was accelerated and kinetic energy is available in flying debris. Only a fraction of the total available energy was taken to break the structure.

Three different mechanismes can destroy a structure at internal detonation: ***composite shock overloading, blastimpulse overloading and gaspressure overloading***. In any case a critical amount of momentum must be transferred to the structural component within a critical time in order to produce a certain failure mode. The fragmentation from composite shock overloading runs on a timescale of about 1 / 1000 of the gaspressure overloading. Nevertheless gaspressure overloading is a rapid event!

- Local ***composite shock overloading*** occurs at contact or near contact detonation. It causes a spall crater, scabbing and penetration. A hole was produced and debris was blown out by an escaping gas flow. The average debris mass is expected to be small.
- Areal ***blastimpulse overloading*** occurs if a whole component was accelerated to a critical velocity so fast that stress concentration at the mountings causes shear or punching failure. Typically a component was torn off in one large piece of debris.
- Volumetric ***gaspressure overloading*** blows the structure up like a balloon. Different modes of failure may happen at gaspressure overloading: "Zippering" due to weak spot or corners, rupture into large sectors like a pressure tank or fragmentation.

The DPM tests were planned to demonstrate that the failure mode changes with increasing loading density and decreasing scaled distance from gaspressure to composite shock overloading. For loading densitiy Q/V < 1 kg/m$^3$ in hardened aircraft shelters the governing process of fragmentation was gaspressure overloading. The empirical data base for DISPRE2 was taken from HAS experiments. Composite shock overloading is the governing mechanisme

at loading density Q/V > 8 $kg/m^3$ in ammunition storage houses. The available data base is rather small.

## 2. Critical Impulse in a Critical Time

A key aspect in the study of detonations is the criterion used as an index for their damage potential. The conventional peak overpressure criterion is deficient in that it predicts the same damage capabilty for both, very short disturbances and for sustained high pressures, provided only that the peak values are the same. Generally the damage inflicted by detonative shock and blast to a target is the result of an impulsive load that exceeds the resistance of a material or a construction. The impulse criterion alone is deficient in that it considers as damaging small overpressures that are applied over a long period and are actually undamaging.

To overcome these difficulties a criterion was suggested in terms of impulse deliverable within a critical time, the *"critical impulse in a critical time"* (Ref. 1; 2). For each target some critical impulse exists above which it is damaged if such impulse was received within a critical time. Below which, there is no effect.

The identification of the critical time within which an impulse must be received by a target in order to have damage inflicted is essentially empirical. However, there are available some guidelines. The critical time must be short compared to the reaction time, otherwise it is not an impulsive loading situation. Sometimes it is possible to estimate the reaction time from basic engineering data.

The criterion also carries within it the important consideration that a minimum overpressure is required to inflict damage to a given structure. This minimum being (2-times) the ratio of the critical impulse to the critical time. For each target some critical peak overpressure exists above which it is damaged, below which, there is no effect.

The critical impulse, the critical time and the critical peak overpressure are very much different for gaspressure-, blastimpulsive and composite shock overloading situations. Nevertheless each of the mechanismes can destroy a structure and cause debris throw.

## 3. Composite Shock Overloading

- Local ***composite shock overloading*** occurs at contact or near contact detonation. Both the shocked air and the detonation products are important in the transfer of mechanical effects. The applied shock overwhelms the material strength and the composite gas flow erodes the material. The component loses locally its material intergrity. A spall crater arises at the frontside and scabbing at the backside. In *overloading* situations the composite shock perforates the component and produces a hole. A large number of small debris is produced and then accelerated by the escaping gas flow.

The distance between the charge and the wall is an important parameter. Composite shock fragmentation of concrete material happens within 5 charge radii for an equivalent spherical, centrically initiated TNT sphere. In general terms composite shock overloading happens within a scaled distance $Z < 0.3$ m/kg$^{1/3}$.

- From the available data it is obvious that composite shock overloading was not an important factor at HAS tests. The loading density was $Q/V < 1$ kg/m$^3$ and the detonating charges at scaled distance $Z > 0.3$ m/kg$^{1/3}$ from the walls. Contrary in the Generic Structure at loading density $Q/V > 8$ kg/m$^3$ up to 75 kg/m$^3$ composite shock overloading will be a governing mechanisme.

An empirical database on the effect of composite shock overloading is needed in order to extent the available DISPRE2 program to high loading situations.

***Some additional remarks according to composite shock overloading:***

The loading density Q/V in terms of charge mass per volume is not the appropriate parameter to describe composite shock overloading situations.

The composite shock causes an impulsive loading situation: A critical impulse must be imparted to the component in a critical time. Velocity is an important parameter. At composite shock overloading a stress wave moves through the material. Associated with the stress wave is the relative particle velocity $v = \sigma / (\rho * C)$. If a critical particle velocity is exceeded, it causes decomposition of the concrete material. So far experimental values are not available for concrete material.

The critical time for composite shock overloading (arbitrarily but reasonably) is taken as the time the shockfront needs to run through the wall thickness. At a shock velocity of $V_s = 4500$ m/s and a wall thickness $t = 0.45$ m the critical time $t_c = 100$ µs. The range of critical time for composite shock fragmentation typically is 10 to 100 microseconds.

Preliminary calculation with SHARC of the reflected pressure-time history at distance $R = 0.5$ m indicates that the scaled composite shock duration $t_+$ typically is $t_+ = 10$ µs/kg1/3. Thus the loading time is in accordance with the critical time typically 10 to 100 microseconds.

Composite shock overloading happens in the regular reflected zone. This was not a result of direct observation. But it is hard to think of this type of reaction in the side-on or the Mach reflection region. A critical peak overpressure exists above which a concrete slab is locally damaged, below which there is no effect. The range of critical impinging shock strength is some 100 MPa peak reflected overpressure.

The idealized, exponential decay blast wave configuration does not apply to the early stages of composite shock in the near zone. The discontinous jump in pressure at the shockfront is followed by a thin lamina of compressed air and detonation products. A secondary shock in

the opposite direction discontinously takes the overpressure close to zero. At a distance of 5 charge radii the pressure-time history rather looks like a rectangel.

Detonative shocks consist of two components: The overpressure component and the gas flow component. The expansion of the detonation products is a significant part of the dynamics in the near zone. The peak particle velocity exceeds 4000 m/s. Close-in about 50 % of the detonation energy is kinetic energy of products and only about 10 % is overpressure energy. It is not only the shock that disintegrates the concrete material. The „jet" of composite gas flow additionally erodes the wall material.

In contact detonations, increasing charge mass is needed to perforate concrete walls of increasing thickness. The shock overpressure at the charge´s surface is independent of the charge mass. More shock impulse must be transferred to the thick wall within a critical time.

If penetration occurs does not only depend on the charge´s mass and distance, but also on the type of high explosive (HE), its shape and the point of initiation.

The fastest pieces of debris, that are observed in experiments are shock produced scabbing debris from the backside or flow driven debris if the component was penetrated.

Hydrocodes may be used to calculate pressure-time histories in the composite shock regime.

## 4. Blastimpulse Overloading

- Areal reflected blastimpulse *overloading* of components typically causes shear failure along fixed edges or restraints. One large piece of debris, wall or roof, is thrown away. The component was accelerated so fast to a critical velocity that stress concentration at the mountings causes shear forces that exceed the material strength. No time was available to dissipate the energy and transform it into plastic deformation. Only a small fraction of the imparted energy was transformed into work done. Most of it is kinetic energy of flying debris.

Experimental verification of this failure mode is available from the excellent photodocumentation of Swiss model tests with aboveground structures and shallow underground structures (Ref.4, Test 3 (0.15 kg/m$^3$), Test 4 (0.3 kg/m$^3$), Test 5 (0.75 kg/m$^3$), Test 6 (1.5 kg/m$^3$), Test 7 (1.5 kg/m$^3$) and Ref. 6 Test No.7). Blastimpulse overloading was simulated in the DPM tests with unrestraint testslabs.

Blastimpulse in this context is the integral of the pressure-time history $i = \int p(t)dt$ of the reflected primary shock measured on the surface of a component from the moment of shockfront arrival. The momentum was transferred to the structural component in a time short compared to the first bending mode. The critical time for blastimpulse overloading typically is 0.2 ms/kg$^{1/3}$ to 2 ms/kg$^{1/3}$. For this mode of fragmentation the available peak overpressure usually exceeds the critical value. Blastimpulse overloading typically happens to a component

at loading density $Q/V > 0.15$ kg/m$^3$ and scaled distance $Z < 1$ m/kg$^{1/3}$. As mentioned earlier, exact figures of critcal loading values do not only depend on loading density and scaled distance. Structural geometry as well as structural and material properties are important.

## 5. Gaspressure Overloading

- Volumetric gaspressure *overloading* blows up the concrete structure like a balloon. It causes bending of components until the concrete breaks under tensile stress. Different modes of failure happen: "Zippering" due to weak spot or stress concentration along corners, rupture into large sectors like a pressure tank or fragmentation. When the structure was fragmented some overpressure remains that accelerates the escaping debris.

In the process of detonation each kilogram of solid high explosive HE produces an additional volume of about 0.7 m$^3$ of hot gaseous reaction products. The rise of pressure within milliseconds is slow compared to composite shock and blastimpulse. Nevertheless is fast enough to prevent the detonation products from escaping through leaks. During the builtup of gaspressure the structural strength can be activated. The reaction will be in the bending mode and thus similar to static overloading of components.

For damage from gaspressure overloading the critical time was taken as one-quarter of the natural period of the first bending mode. The critical time for gaspressure overloading is in the range 10 to 100 milliseconds. Critical overpressure is in the range of 1 MPa to 10 MPa. The size and mass of debris strongly depends on the wall thickness, the type of reinforcement as well as on the quality of construction materials and on the workmanship.

The magnitude and duration of the gaspressure loading phase depends on the charge amount, the internal volume and the vent area. The loading density Q/V, charge mass Q to the chamber volume V ratio, was sucessfully used to empirically describe the destruction in case of gaspressure overloading. If there is a large vent area the gas loading phase is essentially eliminated.

Experimental verification of gaspressure overloading situations is available from the photodocumentation of Swiss model tests. The reinforcement grid was blown up and some concrete debris in the size of the reinforcement mesh was blown out. For aboveground structures the critical loading density was $Q/V = 0.15$ kg/m$^3$ (Ref.5, Test No.1 and Test No.2). For earthcovered structures the critical loading density was $Q/V = 0.4$ kg/m$^3$ (Ref.6, Test No.2 and No.3).

The structures in the HAS, hardened aircraft shelters tests typically were overloaded and destroyed by gaspressure. Photodocumentation from HAS test is available. The distance between the charge and the wall or roof was large enough to avoid composite shock overloading. The momentum that was imparted to the roof by the blastimpulse was not enough to tear it off. Nevertheless the gaspressure was strong enough to blow the structure up and to accelerate the debris. Only part of the total structural mass was thrown away. The structure

collapsed and much of the mass fell to the ground in front of the structure. In DISPRE2 the term "total destroyed mass" was used for the fraction of total mass that was thrown away as dangerous debris.

## 6. DPM Video

A seven minute videofilm is part of the presentation. It describes the DPM program that was done to demonstrate blastimpulsive and composite shock overloading situations. Much of the dynymics of the debris throw can be seen in a film. In order to start a systematic investigation of fragmentation processes the only variable test parameter was the charge mass.

The Debris Program Meppen DPM Phase I was run in Aug/Sep 1995 at the German testsite Wehrtechnische Dienststelle WTD 91 in Meppen. A number of 16 experiments with detonatively overloaded concrete slabs was executed.

A detonation chamber with the inner volume of V = 1 $m^3$ was the basic DPM testarrangement. A concrete slab with the area of A = 1 $m^2$ was placed on top of the chamber. The idea proved to be successful that vertically upwards flying debris can be observed better by cameras than horizontally flying particles.

Two different versions of the basic testarrangement were used: In the closed "C" arrangement the charges were detonated in an underground pit. All walls were made of steelplates that were backed by heavy concrete blocks. It was the idea to have a nonreacting chamber to allow maximum gaspressure builtup.

In the fully vented "V" arrangement the testslab was put as tabletop on a wooden rack. Four sides were open to avoid gaspressure builtup. It was the idea to find out if in composite shock overloading situations the venting does have an effect on the fragmentation.

All testslabs were identical 1 m ∗ 1 m ∗ 0.1 m, made of unreinforced concrete. The slabs were dyed in 3 zones in different colours (red, yellow, green) to allow identification of collected debris.

Semispherical Nitropenta charges were used for all experiments, the charge´s center at R = 0.5 m below the slab center. The ignition was in the charge´s center. The charge mass varied from Q = 1 kg to Q = 27 kg.

The tests were done on a large concrete platform that was cleaned after each test. The debris in each of the collection fields could easily be collected. It was expected that most of the original mass impacts the platform near ground zero to have a high recovery rate. Usually in fieldtests only a small percentage of the destroyed mass can be collected. It was a problem in Meppen that mostly the wind blew at a velocity up to v = 10 m/s. It was not possible to wait for calm wind. The wind had a strong effect on the final debris distribution. From launch to

impact the debris flew up to 40 seconds. In some of the tests all of the debris was blown out of the platform, more than 100 m away from ground zero in the bushes.

The second problem with the debris collection was the tertiary fragmentation in the moment the flying debris impacted the ground. A single slab in flight broke into 4 parts when it fell down from 5 meter hight. Many pieces of debris in flight were disintegrated to aggregate and cement in the moment of impact.

Successful was the High Speed Film at 500 frames per second and High Speed Video at 200 frames per second. The film speed was appropriate to show the overall effects. It was possible to follow single pieces of debris along their trajectories outside the fireball and to determine the launch velocity. In some experiments the maximum height and the total flight time was measured. Both helped to estimate the launch velocity.

In earlier tests only the velocity of the fastest pieces of debris were observed. Slower particles were covered by the fireball and detonation products. Those fastest particles in the DPM tests were identified as "precursor" that transports only a small fraction of the total debris mass. The main mass of debris was launched at lower velocity that could be measured in the DPM tests.

The launch velocity is the most sensitive parameter in DISPRE2 to determine the debris distribution. From the DPM tests additional data on the debris launch velocity for the extended DISPRE2 empirical datsbase are available.

Details and results of the DPM tests will be descibed in Reference 7, which is in preparation.

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